AD-A044 128 ARMY ELECTRONICS COMMAND FORT MONMOUTH N J F/G 9/5

SELF-OSCILLATING MIXERS IN DIELECTRIC WAVEGUIDE.(U)

AUG 77 M M CHREPTA, H JACOBS

UNCLASSIFIED ECOM-4514 NL

1 OF 1

ADA044128

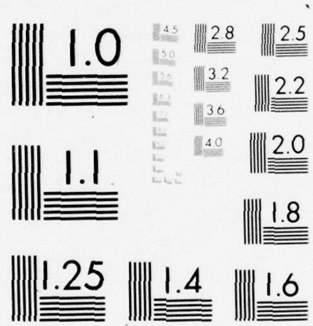
END

DATE

FILMED

10-77

DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

(12)

Research and Development Technical Report
ECOM-4514

AD A044128

SELF-OSCILLATING MIXERS IN DIELECTRIC WAVEGUIDE

Metro M. Chrepta
Harold Jacobs

Electronics Technology & Devices Laboratory

August 1977

DISTRIBUTION STATEMENT
Approved for public release; distribution unlimited.

ECOM

US ARMY ELECTRONICS COMMAND FORT MONMOUTH, NEW JERSEY 07703

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The citation of trade names and names of manufacturers in this report is not to be construed as official Government indorsement or approval of commercial products or services referenced herein.

Disposition

Destroy this report when it is no longer needed. Do not return it to the originator.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: (14) ECOM-4514	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): (6) SELF-OSCILLATING MIXERS IN DIELECTRIC WAVEGUIDE.		5. TYPE OF REPORT & PERIOD COVERED: (9) Research and development technical rept.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): (10) METRO M. CHREPTA, HAROLD JACOBS		8. CONTRACT OR GRANT NUMBER(s): N/A
9. PERFORMING ORGANIZATION NAME AND ADDRESS: US Army Electronics Command, ATTN: DRSEL-TL-IJ, Fort Monmouth, NJ 07703		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: (16) 1T161101A91A, 611101.11.844.45.R6.03
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE: (11) August 1977
		13. NUMBER OF PAGES: 26
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (12) 31p.		15. SECURITY CLASS. (of this report): UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release: Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Self-Oscillating Mixer
Mixers
Receivers
GUNN Diode
Dielectric Waveguide
Integrated Circuits
Millimeter-wave devices
Oscillators

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The feasibility of constructing a single integrated functional device in a dielectric waveguide cavity has been demonstrated. This device is a self-oscillating mixer and antenna consisting of a negative resistance diode imbedded in a high-resistivity dielectric such as silicon or Al_2O_3, with one end of the resonant cavity tapered. This taper serves as an antenna or a coupling element into a standard metal waveguide. Tests have been made at Ku-Band and at V-Band, and it has been found that when used as a receiver, the overall noise

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

037 620

JB

figure is in the order of 10 to 12 dB, including the IF amplifiers. These receivers also provide large bandwidths. The device is simple in construction which predicts low cost and ease in manufacturing. Applications are suggested based on noise figures, minimum detectable sensitivities, and RF power capabilities for systems requiring small size and low cost. These include communications, expendable Electronic Warfare (EW) sensors, radar and short-range terminal homing. These devices may lead to future developments in low-cost millimeter-wave integrated circuits in which entire sections of precision machined metal waveguide structures are eliminated.

TABLE OF CONTENTS

TABLES

FIGURES

SELF-OSCILLATING MIXERS IN DIELECTRIC WAVEGUIDE

ABSTRACT

The feasibility of constructing a single integrated functional device in a dielectric waveguide cavity has been demonstrated. This device is a self-oscillating mixer and antenna consisting of a negative resistance diode imbedded in a high-resistivity dielectric such as silicon or Al_2O_3, with one end of the resonant cavity tapered. This taper serves as an antenna or a coupling element into a standard metal waveguide. Tests have been made at Ku-Band and at V-Band, and it has been found that when used as a receiver, the overall noise figure is in the order of 10 to 12dB, including the IF amplifiers. These receivers also provide large bandwidths. The device is simple in construction, which predicts low cost and ease in manufacturing. Applications are suggested based on noise figures, minimum detectable sensitivities, and RF power capabilities for systems requiring small size and low cost. These include communications, expendable Electronic Warfare (EW) sensors, radar and short-range terminal homing. These devices may lead to future developments in low-cost millimeter-wave integrated circuits in which entire sections of precision machined metal waveguide structures are eliminated.

INTRODUCTION

Self-oscillating mixers have been of considerable interest in recent years (1), (2), (3), due to the fact that they embody simplification for the circuitry of receivers. In more conventional mixers, there usually exists a signal frequency, a mixer diode of a rectifier type, and a separate local oscillator. In conventional mixer theory, if the local oscillator voltage is

$$e_o = E_o \cos \omega_o t, \qquad [1]$$

the instantaneous conductance of the diode is

$$g = A_o + \sum_{n=1}^{\infty} A_n \cos n\omega_o t \qquad [2]$$

where the coefficients are determined by the shape of the conductance characteristics of the mixer and ω_o is the fundamental frequency of the local oscillator (LO).

Assuming a high crystal resistance, the current determined by the impedance of the crystal is given by

$$i_b = ge_s \qquad [3]$$

where e_s is the signal voltage. If the signal is an unmodulated sine wave, the current for $e_s = E_s \sin \omega_s t$ is

$$i_b = A_o E_s \sin \omega_s t + E_s \sum_{n=1}^{\infty} A_n \cos n\omega_o t \sin \omega o t \qquad [4]$$

$$\text{or, } i_b = A_o E_s \sin \omega_s t + \frac{E_s}{2} \sum_{n=1}^{\infty} A_n [\sin(\omega_s + n\omega_o)t + \sin(\omega_s - n\omega_o)t] \qquad [5]$$

The final term contains the IF. Conversion can take place with the fundamental frequency of the local oscillator (n=1) or any higher value of n. Modulation sidebands can occur with frequencies

$$(\omega_s - n\,\omega_o + \omega_m), \quad (\omega_s - n\omega_o - \omega_m).$$

In the self-oscillating mixer, the mixer diode is eliminated. That is, a Gunn diode (or BARITT diode) will serve both as a local oscillator, and because non-linearities are always present in an oscillator, as a mixing element. In the latter arrangement, the signal is fed directly into the oscillator and a suitable IF probe will remove the IF power for use in subsequent amplifier stages; thus, the whole mixer assembly, as well as certain associated filters, may be eliminated. Self-oscillating mixers have been developed in metal waveguides for Doppler radar and are becoming commercially available. Early work on self-oscillating mixers was hampered by the fact that the noise was considerably higher than that of conventional mixers limiting the applications to short range radar where considerable noise levels could be tolerated. This accounts for the early emphasis on only short range Doppler radar (4) where the IF frequencies are relatively low, i.e., about 100 KHz or less. The question of noise at higher IF frequencies is another matter. Lazarus indicated that at 60 MHz, using 33 GHz Gunn diode oscillators, a noise figure of 19dB was observed with an IF bandwidth of 32.5 MHz. While this is not a low-noise figure by mixer standards, it could be of importance if further improvements in noise figure were attained. One of the objectives of this report is the determination of noise figures of self-oscillating mixers. Another objective of the investigation was to determine if considerable simplification, and hence reduction in cost, could be attained. In the quest for lower cost, the dielectric waveguide (or image-line) technology was applied using a Gunn diode in a simply constructed cavity, in a self-excited oscillator-mixer mode of operation. The significance of this technology is that active devices, as well as passive components, can be developed in circuit modules to construct functional subsystems. With the indicated improvements in cost and performance, new applications appear possible for expendable sensors and jammers, proximity fuses, short-range guidance sensors, communications and radar receivers.

In the course of this work, devices were designed, constructed, and evaluated for X-Band, Ku-Band and V-Band. The general construction is illustrated in Figure 1. Note that a Gunn diode was imbedded in an aperture

which was cut in a high resistivity silicon or Al_2O_3 ceramic waveguide. A resonant transformer disc was used to couple the energy of the diode into the dielectric waveguide system. At the far end is a tapered waveguide acting as an antenna. The configuration served as a combined functional device containing an antenna for incoming signals, a self-oscillating mixer diode, and with the help of a bias and coaxial lead for the IF, could be studied as a mixer for a superheterodyne receiver.

OSCILLATOR CIRCUIT

In discussion of the oscillator, consider first some general theories developed by Kurokawa.[5] Any stable microwave oscillator circuit can be represented by an equivalent series resonant circuit, as shown in Figure 2. The diode is represented by a device with impedance $\overline{R} + j\,\overline{X}$. The cavity resistance, capacitance and inductance, is represented by the elements R_i, C and L and the output power is developed across a load resistance, R_o. The signal generator is represented by a voltage, e(t), which can be a small signal or a source of noise. Postulating a current which can change amplitude or phase with respect to time, Kurokawa then develops differential equations, the solutions of which, give amplitude and phase and are

$$\left(L + \frac{1}{\omega^2 C}\right)\frac{dA}{dt} + (R_i + R_o - \overline{R})\,A = \frac{2}{T_o}\int_{t-T_o}^{T_o} e(t)\cos(\omega t+\varphi)\,dt \qquad [6]$$

$$\left(-\omega L + \frac{1}{\omega C} - \overline{X}\right) - \left(L + \frac{1}{\omega^2 C}\right)\frac{d\varphi}{dt} = \frac{2}{A T_o}\int_{t-T_o}^{T_o} e(t)\sin(\omega t+\varphi)\,dt, \qquad [7]$$

where A(t) is the amplitude of the current, (φ) is the phase, T_o is the period, and e(t) is the signal voltage. Under the conditions of steady state oscillations,

$$e(t) = 0, \quad \frac{dA}{dt} = 0, \quad \frac{d\varphi}{dt} = 0.$$

In this oscillating condition,

$$\overline{R} = Ri + Ro \qquad [8]$$

and

$$\overline{X} = \frac{1}{\omega C} - \omega L, \qquad [9]$$

where $\overline{R}$ is the magnitude of the negative resistance of the diode and $\overline{X}$ is the magnitude of its reactance.

In practice, in metal waveguide circuits, after some approximation of these characteristic values, the diodes are placed in a metal walled oscillator cavity. The cavity dimensions are varied by tuner element; the diode can be biased for optimum oscillator characteristics for the conditions required to meet the stable oscillation criteria. Both $\overline{X}$ and $\overline{R}$ are

dependent upon the frequency and amplitude of the oscillation. In the case of the dielectric waveguide oscillator, the circuit matching is accomplished in a manner similar to the metal waveguide case. It can be shown that the dielectric oscillator can be designed to approximate dimensions. In order to test the device as a self-oscillating mixer, the pointed section is placed in a standard waveguide and positioned for maximum transfer of power. When the adjustments are completed, it is equivalent to changing the coupling into the metal waveguide and hence adjusting R_0 with concurrent smaller changes in the other equivalent components in the circuit.

Still another concept used which is in current practice, and which is derived from Kurakawa's presentation. This concept occurs in the experiment referred to as the measurement of the external Q (or Q_{ext}) by the method of frequency pulling. It can be assumed that the signal generator is applying a small voltage e(t) at an angular frequency ω, nearly equal to the resonant frequency ω_0. The frequency of the oscillator will be pulled into the frequency ω. If the frequency is moved farther away from ω_0, or if the power from e(t) is decreased, there will be a sudden change in frequency and the oscillator will snap back to ω_0, and mixing products will occur. The total frequency range of pulling will be called $|\Delta\omega|_{max}$ from $\omega-\omega_0$ to $\omega+\omega_0$. The end result of the analysis is given by the following approximation for the synchronizing frequency range:

$$|\Delta\omega|_{max} = \frac{2\omega_0}{Q_{ext}} \left(\frac{P_s}{Po} \right)^{1/2}, \qquad [10]$$

where $|\Delta\omega|_{max}$ is the total range of pulling, ω_0 is the resonant frequency of the oscillator diode and cavity; P_0 is the "power out" of the free running oscillator across the load R_0, and P_s is the available power from the synchronizing source e(t).

OSCILLATOR DESIGN

The oscillator cavity design is based on an image-line concept first formulated by Marcatili(6) and later modified for millimeter waves.(7)(8) First, consider propagation of an electromagnetic wave in a dielectric waveguide. The fundamental wave will propagate as shown in Figure 3, and in the E^y_{11} mode, a hybrid mode which propagates when correctly launched. The propagation characteristics are given by the following approximations:

$$k_x = \pi/a \left(1 + \frac{A_3 + A_5}{\pi} \right)^{-1} \qquad [11]$$

$$k_y = \pi/b \left(1 + \frac{n_2^2 A_2 \; n_4^2 A_4}{\pi \, n_1^2 \, b} \right)^{-1} \qquad [12]$$

$$\xi_{3,5} = 1/\left(\left[\frac{\pi}{A_{3,5}} \right]^2 - k_x^2 \right)^{1/2} \qquad [13]$$

$$\eta_{2,4} = 1/ \left(\left[\frac{\pi}{A_{2,4}} \right]^2 - k_y^2 \right)^{1/2} \qquad [14]$$

$$A_{2,3,4,5} = \lambda_o/2 \; (n_1^2 - n_{2,3,4,5}^2)^{1/2} \qquad [15]$$

$$k_z^2 = k_1^2 - k_x^2 - k_y^2 \qquad [16]$$

$$k_z = 2\pi/\lambda_g \qquad [17]$$

where $k_{x,y,z}$ = propagation constant in x,y and z direction,

$1/\xi_{3,5}$ = attenuation constant in media 3 and 5 (air)

$1/\eta_{2,4}$ = attenuation constant in media 2 and 4 (air)

k_1 = propagation constant in bulk dielectric

n_1 = index of refraction in dielectric medium

λ_g = guide wavelength

λ_o = wavelength in air

a = the width of the dielectric

b = the height of the dielectric

In applying the above equations to a silicon guide, cut to a little less than one wavelength in the medium in width, and less than one-half wavelength in height, the guide wavelength can be calculated by:

$$\lambda_g = \lambda_o / n_{eff} \qquad [18]$$

where n_{eff} is approximately 3.0 instead of 3.464. In the experiments described below, the cross-sectional dimensions of all X-Band and Ku-Band dielectric oscillators were cut to the approximate dimensions indicated above. At 60 GHz, cross-sectional dimensions of the dielectric guides were oversized, i.e., slightly greater than 1 millimeter in height and about 2 millimeters in width. Experiments indicated that even in this oversized condition, the E^y_{11} mode dominated.

In the construction of the oscillators, and in their design to produce an operational frequency, three factors had to be considered in the following order of importance as shown in Figure 4.

1. The specific frequency (related to transit time and packaging) of the diode had to be selected for a given frequency of operation.

2. In all cases, a metallic resonant transformer disc was used on top of the dielectric, making contact with the diode to provide tuning.

3. The resonant length of the dielectric section, in back of the diode, was chosen for optimum power. This was approximated to be(2n+1) in length.

Although the diodes oscillated without metal shielding, a metal enclosure was constructed surrounding the diode. This enclosure was constructed in order to prevent radiation from the diode to the adjacent area or to prevent unwanted signals from entering from outside the oscillating region.

In summary, for the performance characteristics of the dielectric oscillator and antenna, and indicated construction, the transmission line equivalent circuit and the lumped constant series resonant equivalent circuit, shown in Figure 5, were postulated.

ELECTRICAL MEASUREMENTS

Measurements were made at Ku-Band, X-Band and V-Band on the dielectric oscillators.

Further discussion of the concepts and data related to Q_{ext} follow. Another definition of the external Q is 2π times the peak energy storage, divided by the energy dissipated per cycle in the load, i.e., $\omega L/R_0$. This is in contrast to the unloaded Q which is defined as 2π times the peak energy storage, divided by the energy dissipated per cycle in the cavity structure itself, i.e., $Q_u = \omega L/R_i$. In metal walled cavities, Q_u is determined largely by the conductivity of the walls (skin effect), by dissipation due to non-uniformities, discontinuities in the walls, and similar practical considerations. Thus, the Q_u values are related to the unloaded properties of the cavity. The Q_{ext} value will be a function of the power released from the system and hence is dependent upon the coupling to the system outside of the cavity. In most circuit considerations such as noise, frequency pulling, and power output, it is usually the Q_{ext} which is of prime consideration.

In these experiments, measurements were made of Q_{ext} using the circuit in Figure 6. The oscillator consisted of a Gunn diode inserted in a dielectric of high resistivity silicon or Al_2O_3 ceramic with a pointed end. The oscillator was shielded with a metal cover to prevent radiation from outside the oscillator entering the system. The pointed end of the dielectric was then inserted into the metal waveguide for measurements. The output power, P_0, could be measured with a power meter and the frequency monitored by the spectrum analyzer. Note that the physical depth of insertion of the pointed dielectric, was adjusted for the maximum power output from the oscillator. The signal was then injected from the sweep oscillator through a calibrated attenuator so that the power input could be determined, as well as the variation in frequency from the signal source (sweep oscillator). Thus, $|\Delta f|_{max}$ could be obtained by varying the frequency through the entire range of pulling, as noted on the spectrum analyzer monitoring P_0. At the end of the frequency pulling range, an abrupt change in the output frequency occurs as the oscillator jumps from the pulling frequency into mixing and a large number of mixing products appear. Tests were run in the region of 14 to 17 GHz and typical data is given in Figure 7. Here, $Q_{ext} = 640$, at an oscillator frequency of 14 GHz and a P_0 in the order of 50 mW. Other data, not shown here, indicated Q_{ext} values in the range of 300 to 640 for pointed dielectric resonators in the Ku-Band region of frequencies. The external Q described here is quite high and comparable with values of Q_{ext} in metal walled Gunn diode cavities with iris coupling to the metal waveguide. In other investigations, which will be reported in more detail in a future report, investigation was made of Q_{ext} at 10 GHz. Here, the resonator structures were constructed differently, i.e., they consisted of rectangular sections of dielectric cut perpendicularly on both ends. As an additional variation, a dielectric image line of considerably longer length than the cavity, was used as a transmission line and inserted about 3 millimeters into X-Band metal waveguide for maximum power transfer and to make the frequency pulling measurements. The dielectric image line extension was approximately 10 cm in length so that the dielectric rectangular resonator was located at a physical distance slightly greater than 10 cm from the waveguide opening. In these experiments, P_0 was 56 mW, f_0 was 10.61 GHz, and Q_{ext} was found to range in values from 118 to 140. Conclusions from these experiments indicated that Q_{ext} was sufficiently high to be useful for Gunn diode oscillator applications.

In all of these experiments, Equation [10] was used to make the calculation of $|\Delta f|_{max}$ (or the equivalent $|\Delta\omega|_{max}$). The conditions for stable oscillation may be enhanced in a dielectric resonator due to the high circuit capacitance, C, for high stored energy and the absence of dissipation due to skin effect losses associated with metal walled cavities. This may be seen by rewriting the equation for Q_{ext} as:

$$Q_{ext} = \frac{\omega\,(C+C_0)}{G_L} \qquad [19]$$

for a parallel equivalent circuit where C is the capacitance of the cavity, C_O is the capacitance of the diode and G_L is the conductance of the load which includes not only the effect of the output coupling, but in addition, any dissipative effects inside the cavity.

The next subject to be discussed is the measurement of noise in the self-oscillating mixer.

The noise figure was measured at Ku-Band using several different techniques, i.e., a gas-discharge tube-noise test set, comparison with conventional mixer diode noise performance using a klystron local oscillator, and the method of minimum detectable signals (MDS). MDS gave the greatest reproducibility and validity, and was used extensively in this work for both Ku-Band and V-Band tests. Also of interest was the measurement of conversion loss or gain (P_{IF}/P_S), the ratio of IF power to signal power. The basic test circuit used is shown in Figure 8. Modifications of this circuit were appropriately used. Two separate and complete test benches were used, one for Ku-Band and the other for V-Band. The signal was introduced on the left by a sweeper or signal generator, both of which could be used with square-wave modulation. A wavemeter was used to determine the frequency of the signal and a calibrated attenuator provided desired power levels, P_S. The signal was then fed into the dielectric image-line oscillator mixer. The power output, P_O, of the oscillator was measured, as well as its frequency, by means of the circulator, second wavemeter, a thermistor and power meter. The bias to the diode was supplied by a constant current power supply through a series-connected inductance. The IF output was fed into selected types of IF amplifiers and then to an oscilloscope or power-measuring device for the particular IF frequency. To insure maximum coupling of the signal power into the oscillator, and simultaneously the maximum power out of the oscillator, the depth of the pointed end of the dielectric was adjusted for maximum P_O. To measure the MDS, the input power was supplied by the calibrated source and was swept in frequency, or square wave modulated, at a particular frequency. With the oscillator on, the IF power was monitored with the oscilloscope. The input power was decreased until

$$\frac{P_S + N}{N} = 2 \qquad [20]$$

The value of the signal power in this condition is defined as P_{min}. The noise figure is established as

$$NF = \frac{P_{min}}{kTB}, \qquad [21]$$

where B is the bandwidth of the IF amplifier and $kT = 4 \times 10^{-21}$ W/Hz. Converted to dB, this equation is often written as

$$NF_{dB} = P_{min}\ (\text{dBm}) + 174\ (\text{dBm}) - BW\ (\text{dB}). \qquad [22]$$

All noise figures quoted in this arrangement refer to total receiver noise figure, including the IF amplifier.

Several IF amplifiers were used, but in most cases, an amplifier centered at 300 MHz with a 100 MHz bandwidth was applied (the ICLT - 300). Repeatable results were obtained at Ku-Band, particularly in the region of 15 GHz to 18 GHz, giving a minimum detectable signal of -82 dBm. By applying Equation [22], a total receiver noise figure of 12dB was attained. It was further noted that due to using an appropriate inductance in the bias lead, the MDS was broad in frequency range and did not show any resonant spikes. This was ascertained by applying the Ku-Band sweeper as indicated in Figure 8. In another arrangement, to test the effect of the IF amplifiers, the IF output from the oscillator mixer was fed into a TRONTECH L300F amplifier, followed by the ICLT 300 amplifier. The L300F had a center frequency of 300 MHz, 3dB bandwidth points of 175 and 450 MHz, a gain of 30.5dB, NF = 1.2dB, VSWR (input) = 1.3, VSWR (output) = 1.8. Often, during these experiments even lower MDS values, i.e., -84dBm, or 10dB NF were observed, but the value of 12dB is given as being consistent over a broad range in frequencies. It was noted that the NF value is a low value, only a few dB greater than a standard mixer diode (about 6.5dB). It was also noted that the low-noise figure occurred at low bias voltage, i.e., 4.5 to 6.0 volts on a diode specified at 10 volts for normal oscillator bias. It was found that these diodes in the self-oscillating mixer configuration displayed conversion gain when the bias voltage was reduced to the abovementioned values. In a series of tests, the conversion gains were found as listed in Table I.

TABLE I: CONVERSION GAIN AS A FUNCTION OF RF SIGNAL POWER, f_O = 15.95 GHz, P_O = 24 mW.

SIGNAL POWER	CONVERSION GAIN IN dB
-80dBm	16.5
-76	13.0
-68	14.0
-64	15.0
-60	17.0 *
-50	13.0
-44	14.8
-40	14.8
-30	14.8
-20	15.2

*P_O = 12 mW

It can be concluded from this experiment that there was a large dynamic range, i.e., the conversion gain does not change much as a function of signal input power.

Another item of concern is the IF bandwidth of the self-oscillating mixer. In the next experiment, efforts were made to measure the bandwidth. In many applications it is desirable to have a uniform response over a large range of frequencies. In this case, the full bandwidth of the IF amplifier was chosen as the goal, i.e., about 200 MHz, or in the range of 200 to 400 MHz. A typical data curve is illustrated in Figure 9. In this figure, f_O is centered at 15.23 GHz. The IF generated is due to the difference frequency $f_S - f_O$ on the left, and $f_O - f_S$ on the right. The attenuation at the center is due to the passband characteristic of the IF amplifier. On the right side, as the RF signal reaches 14.81 GHz, the amplifier passes the IF signal and at 15.03 GHz the IF is again cut off. This gives a range of IF at about 220 MHz, the full passband of the IF amplifier. A similar result is obtained on the left side of the curve where the signal frequency is higher than the local oscillator frequency. For this test, the IF amplifier used was the ICLT-300 specified with a passband from 200 to 400 GHz. This particular diode was operated at a relatively high bias voltage (8 volts) with a resulting conversion loss of 10dB over the 220 MHz band. As a result of the 8 volt bias, the minimum detectable signal was about -75 dBm over the 220 MHz bandwidth. This experiment indicates that the self-oscillating mixer in a dielectric waveguide has a wide bandwidth response. All of the data described above were taken with oscillator cavities that were designed and are illustrated in Figure 4.

The following pertains to measurements made at 60 GHz. Oscillators had been designed and constructed using the general configuration shown in Figure 4 at 10 GHz, 14-18 GHz, 22-24 GHz, and 34-36 GHz. In working at 60 GHz however, it was found to be necessary to modify the design in order to prevent more serious leakage losses due to openings in the structure of the shield. Radiation losses through openings now became more apparent. A new configuration modification was designed and constructed and is shown in Figure 10. The tapered end of the dielectric resonator was inserted into the V-Band waveguide so that the openings were minimized; the probe for the IF output was followed by an RF choke and the bias lead, consisting of a thin copper ribbon, was connected separately from the IF system. This bias ribbon had to be of critical length so as not to present an RF short to the diode. It was considered that the lead should be an odd quarter-wavelength in length so that the diode, looking into the bias line, would see an infinite impedance. A Varian 60 GHz Gunn diode was mounted in an alumina waveguide resonator using the image guide configuration illustrated in Figure 10. The circuit is shown in Figure 8. The dielectric waveguide oscillator was coupled to the metal waveguide via the dielectric taper, which can effect a low loss match to the metal waveguide by sliding the tapered end into the metal waveguide for maximum power indication. This matching condition also yielded optimum IF output when the RF input signal was introduced. Gunn diodes, with manufacturers' data of 10mw output power or less were used. The only other way that the oscillator power could be varied was by bias voltage, which also varied the frequency of oscillation. With an RF input signal introduced through the circulator, the difference signal was extracted via the coupling capacitor, shown in Figure 10. This IF power was measured and compared to measured values of RF input power varied by the precision attenuator for conversion gain (loss) measurements.

Conversion gains were measured up to 15dB; however a value of approximately 5dB was held for the experiment.

In these series of measurements, data were taken with the TRONTECH W-110B IF amplifier, useful in IF frequencies ranging from 1 to 120 MHz. This device had a 50dB gain and a 1.2dB noise figure. The Gunn diode provided an LO frequency of 60.78 GHz, and an output power, P_o, of 0.1 mW. An MDS in the range of -80dBm to -84dBm was found over the IF frequency band, indicating an overall receiver noise of 10dB to 14 dB. (With further adjustment of bias of the diode and depth of insertion of the taper into the V-Band metal waveguide, a sensitivity of -90dBm was observed). Using Equation [22], and a bandwidth of 80dB (100 MHz), this yields a total receiver noise figure of 4dB. This unusually low noise figure was checked several times. The IF amplifier and detector diode were also checked as were the other components in the system. No discrepancies were found. Conclusions from these experiments were that the noise figure at 60.78 GHz was generally in the range of 10 to 14 dB over the full passband of the IF amplifier, and that by a careful circuit adjustment, a noise figure of 4 dB was obtained.

In measuring conversion gain at 60 GHz, there were only slight fluctuations in gain as a function of frequency. The frequency behavior of conversion gain is shown in Figure 11. Here, the power output of the Gunn diode was again 0.1 mW at a frequency of 60.78 GHz with the conversion gain set at 5 dB. The frequency range over which conversion gain was measured was from 1 to 110 MHz and was limited by the IF amplifier. Although the Gunn diode bias was only about 3.5V (compared with 5.0V recommended for higher power operation), no instabilities were observed. Conclusions were that Gunn diodes can be used as a self-oscillating mixer in stable operation at 60 GHz, with conversion gain and fairly low noise figures.

INTERPRETATION

A comparison is offered of the data obtained in these experiments with results obtained by other investigations in the area of self-oscillating mixers. For this comparison, data, for the dielectric oscillator, indicates receiver noise figures of 10 dB to 12dB over an information bandwidth of 100 MHz.

In a report by Albrecht and Bechteler(9), noise figure measurements and conversion loss were measured in metal waveguide structures. Noise figures of roughly 22dB to 40dB were measured for the oscillating mixer. By particular emphasis of the matching of the signal RF into the metal-walled cavity, the lower figures of 22dB were obtained. All data were taken at X-Band, with f_{IF} in the range of 10 to 90 MHz. The investigation predicted 10 - 15dB should be realizable - but gave no calculations or results that would support this contention. The most significant aspect of their paper is that they placed great emphasis on obtaining proper matching of the signal power into the oscillator cavity.

Following this, significant experiments were reported by Lazarus, Bullimore and Novak [10]. They reported a sensitivity of -80dBm at 33 GHz, with IF at 60 MHz and an IF bandwidth of 32.5 MHz as a best result. This corresponds to a noise figure of 19 dB. They also reported a conversion gain of about 3dB at this most sensitive point, the conversion gain decreasing slightly with increasing signal input power. The value of 19dB noise figure was the lowest reported in the literature but is still considerably higher than the noise figure reported in these experiments. In the report by Lazarus et al. no mechanisms were suggested, but their techniques indicate that they were well aware of Albrecht's work and the emphasis on matching.

More recently, and in parallel with these investigations, Webber and Kofol [11] have studied dielectric waveguide, image-line, self-oscillating mixer performance. The design of their cavity structure utilized a metal-backed dielectric rectangular structure, the diode being imbedded in the dielectric, near the center. Following this, they inserted a metal aperture in the dielectric line for coupling to an insular line waveguide output line. They demonstrated this type of dielectric oscillator as a transmitter and as a self-oscillating mixer with FM capabilities and, in fact, were able to show feasibility of an FM system operating at 46 to 48 GHz using commercial (Microwave Associates) Gunn diodes. Their main emphasis was aimed at the development of a subsystem. As a result, not enough time was available for a study of the lowering of the receiver noise figure. In their FM receiver however, they demonstrated the following noise properties. At f_{LO}= 46.850 GHz, they measured a conversion loss of 4dB. The mixer noise figure measured for a 300 KHz information bandwidth was approximately 28dB, including a 3dB noise figure contribution by the preamplifier. Other data in their report indicate that for a conversion loss near unity, the noise figure was about 24dB. The center IF frequency was 160 GHz $\pm$ 30 GHz. In summary, they have found overall receiver noise figures in the range of 24 to 28 dB.

Other values of noise figure have also been reported for Doppler radar applications. Oscillators are, in fact, now commercially available with a Gunn diode in a metal walled cavity at X-Band. These measurements of noise figures are not relevant to this discussion since they necessarily operate at very low IF frequencies. The primary consideration here may be 1/f noise which starts at about 100 KHz and increases rapidly with decreasing frequency. Haddad [12] has successfully carried out experiments indicating the BARITT diode may be better applied here for self-oscillating mixer developments than the Gunn diode. In these experiments, and the references quoted, concerns with IF frequencies well out of the 1/f region, were excluded from consideration.

Conclusions, from surveying the literature, were that these results give noise figures (10 to 12dB) which are significantly lower than data previously reported (19dB to 25dB) for self-oscillating mixers using Gunn diodes with IF frequencies well beyond the 1/f region of noise. There are two conditions however, which must be met to achieve low noise. These are described as follows: First, the IF frequencies must be high, in the region of 1 MHz to 300 MHz or higher. If one considers the noise-to-oscillator power ratio of the Gunn diode, the injected signal must not be buried in the noise of the oscillator. This principle has been discussed by Kotani [13] and has been generally applied in many other kinds of mixers including the

subharmonically-pumped mixer developed by Schneider.(14) Second, the original concept proposed by Albrecht of impedance matching is significant. In the designs shown in both the Ku-Band and V-band dielectric oscillators, tuning could be accomplished not only by resonant transformer discs, lengths of dielectric line (cavity length) and back reflectors, but more significantly, could be further accomplished by varying the depth which the pointed end of the dielectric could be inserted into the open waveguide. Generally, the taper was inserted for optimum coupling from the oscillator to the waveguide for maximum power transmission. If the signal input power were sufficiently close to the local oscillator power, but distant enough not to be in the 1/f noise region, by reciprocity, a maximum transfer of signal power into the oscillator system at the same physical location of the taper, could be expected. Experimentally, findings indicated that the minimum detectable signal was sensitive to this positioning. Thus, a mechanical means of tuning the input in a manner analogous to that proposed by Albrecht, was used for the dielectric oscillator-mixer. The difference being that Albrecht had suggested, in his metal waveguide system, an EH Tuner, while in the experiments described in this report, the transforming properties of the taper position was utilized. There are still factors, other than the two mentioned above, the importance of which may be considered in the future. These include the role of the Q of the dielectric cavity, and the role of the Gunn diodes themselves.

CONCLUSIONS AND APPLICATIONS

Self-oscillating mixer assemblies have been designed and constructed using Gunn diodes imbedded in dielectric waveguide oscillators. One end of the dielectric was tapered so as to fit into a standard waveguide for measurements. The oscillator dimensions were designed with the following considerations:

1. The diode must be selected for the desired frequency of operation.

2. Resonant transformer tuning discs were used.

3. The dimensions of the dielectric were suitable for efficient oscillations.

Further tuning was obtained by adjusting the depth of the taper in the metal waveguide.

Upon testing at Ku-Band and V-Band, low noise figures were obtained (in order of 10 to 12dB) with frequencies ranging from 1 MHz to 120 MHz and 200 MHz to 400 MHz, and noise bandwidths of about 100 MHz. In comparing these values with other investigations, it appears that these noise figures are about 10dB better than previously reported. In addition, the bandwidths are sufficiently broad to be useful in military systems.

With regard to applications, when using an isolator or circulator in front of this mixer, the simple construction may result in low-cost devices used as receivers for expendable EW sensors, communications, radar and short-range terminal guidance. Without the presence of the isolator or circulator,

the device may have applications in fuzes and proximity sensors. Many of the same principles can be applied to other negative resistance devices such as the BARITT diode, the IMPATT diode, the TUNNETT diode with particular applications compatible with their frequency, power and noise characteristics.

REFERENCES

(1) S. Kwok, H. Nguyen-Ba and G.I. Haddad, "Properties and Potential of BARITT Devices". Proceedings of the International Solid-State Circuits Conference, pp 180-181, Feb 1974.

(2) M.J. Lazarus, S. Novak and E.D. Bullimore, "A Sensitive Millimeter-Wave Self-Oscillating Gunn Diode Mixer", Proc. IEEE, Vol. - pp 813-814, May, 1971.

(3) M. Kotani and S. Mitsui, "Self-Mixing Effect of Gunn Oscillator", Electronics and Communications in Japan, Vol. 55-B, No. 12, pp 60-67, 1972.

(4) Nygren and Sjolund, "Sensitivity of Doppler Radar with Self-Detecting Diode Oscillators", IEEE Trans. Microwave Theory Tech., Vol. MTT-22, May, 1974.

(5) K. Kurohawa, "Some Basic Characteristics of Broadband Negative Resistance Oscillator Circuits", Bell System Tech. J., Vol -- pp 1937-1955, July-August, 1969.

(6) E.A.J. Marcatili, "Dielectric Rectangular Waveguide and Directional Coupler for Integrated Optics", Bell System Techn. J., Vol 48, pp 2071-2102, Sept, 1969.

(7) K. Klohn, J. Armata, M.M. Chrepta, "Transverse Propagation Constants in Dielectric Waveguides", US Army Electronics Command, Fort Monmouth, NJ Tech Rpt 4242, August, 1974.

(8) H. Jacobs, G. Novick, C.M. LoCascio, M.M. Chrepta, "Measurement of Guide Wavelength in Dielectric Rectangular Waveguide", Proc. IEEE, Vol MTT-24, pp 815-821, November, 1976.

(9) A. Albrecht, M. Bechteler, "Noise Figure and Conversion Loss of Self-Excited Gunn Diode Mixers", Electron Letters, Vol 6, No. 11, pp 321-322, May, 1970

(10) IBID (2)

(11) G.E. Webber, J.S. Kofol, "Millimeter-Wave Dielectric Waveguide Integrated Circuits", Contract DAAB07-75-C-1317, July 26, 1976.

(12) J.R. East, Hien Nguyen-Ba, G.I. Haddad, "Design, Fabrication and Evaluation of BARITT Devices for Doppler Systems Applications", IEEE Trans. Microwave Theory Tech., Vol MTT-24, No. 12, pp 943-948, Dec, 76.

(13) IBID (3)

(14) W.W. Snell, M.V. Schneider, "Millimeter-Wave Thin-Film Down-Converter", IEEE Trans. Microwave Theory Tech., Vol MTT-24, No. 11, pp 804-806, November, 1976.

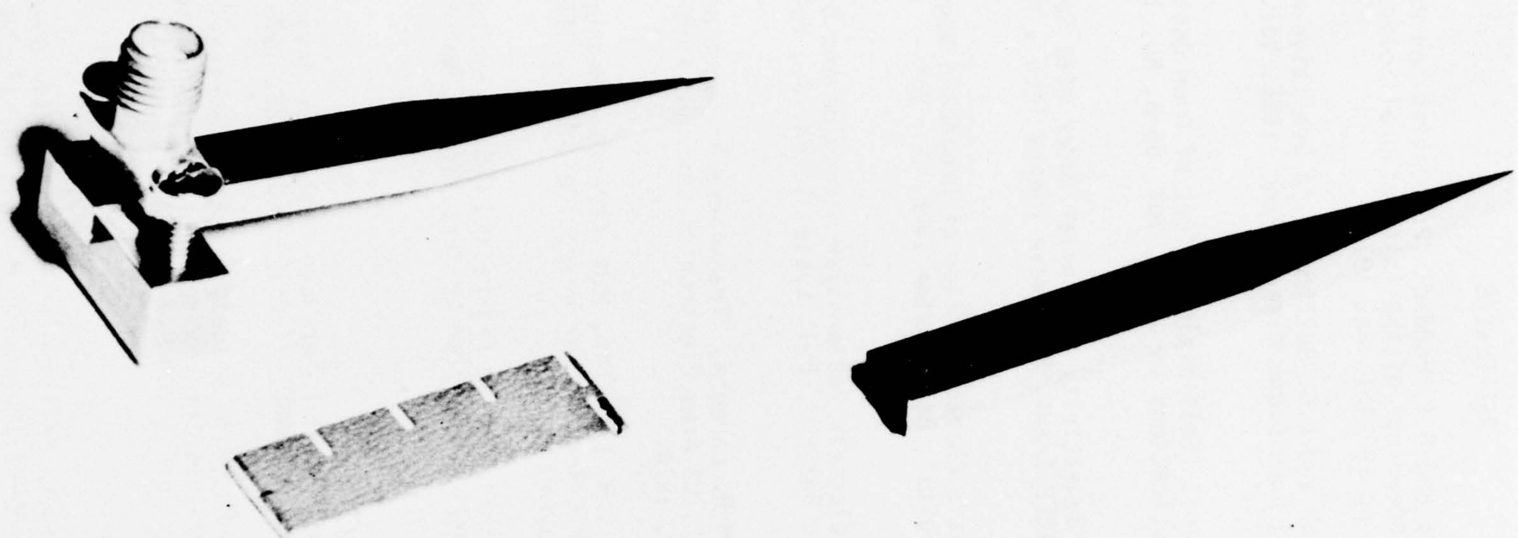
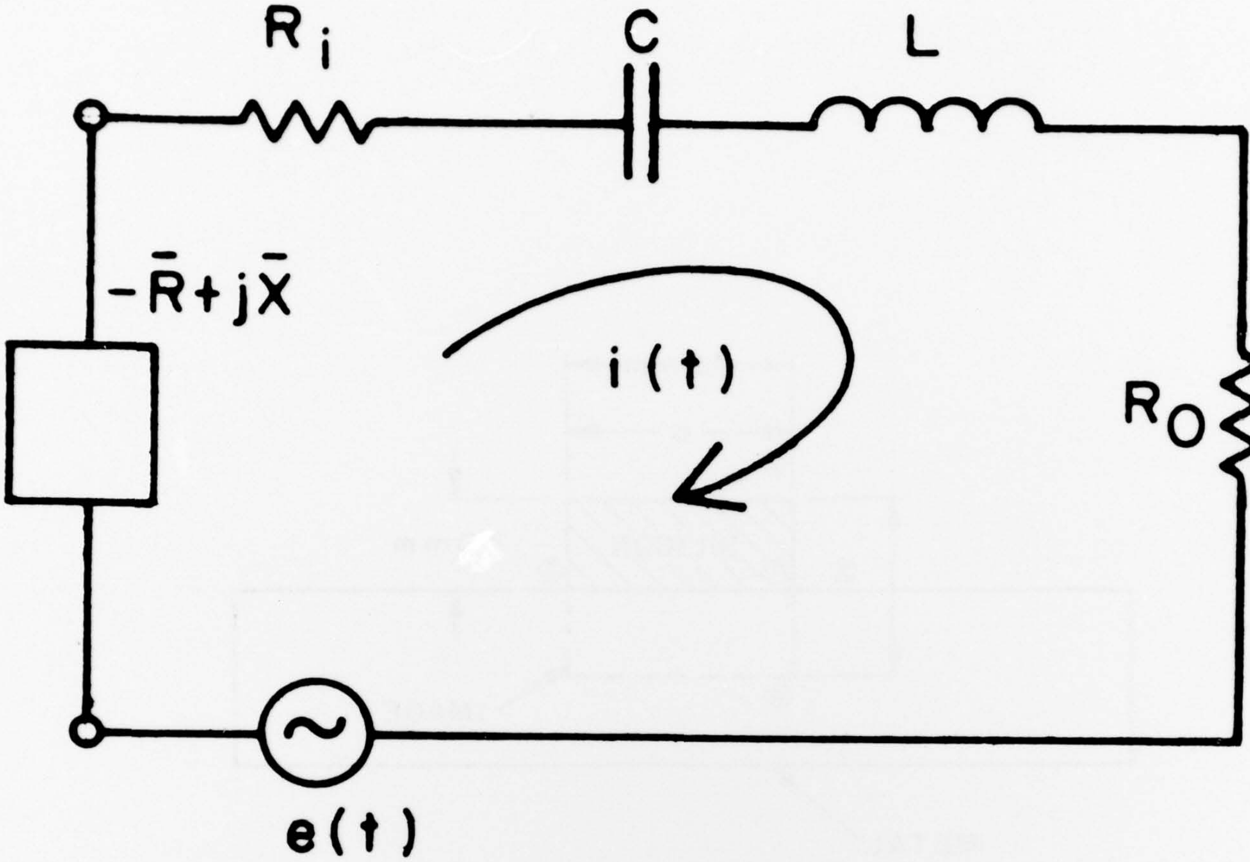


Figure 1. Ku-Band Self-Oscillating Mixer



$$\omega_O = \frac{1}{\sqrt{LC}} \qquad Q_{ext} = \frac{\omega_O L}{R_O}$$

Figure 2. Oscillator Equivalent Circuit

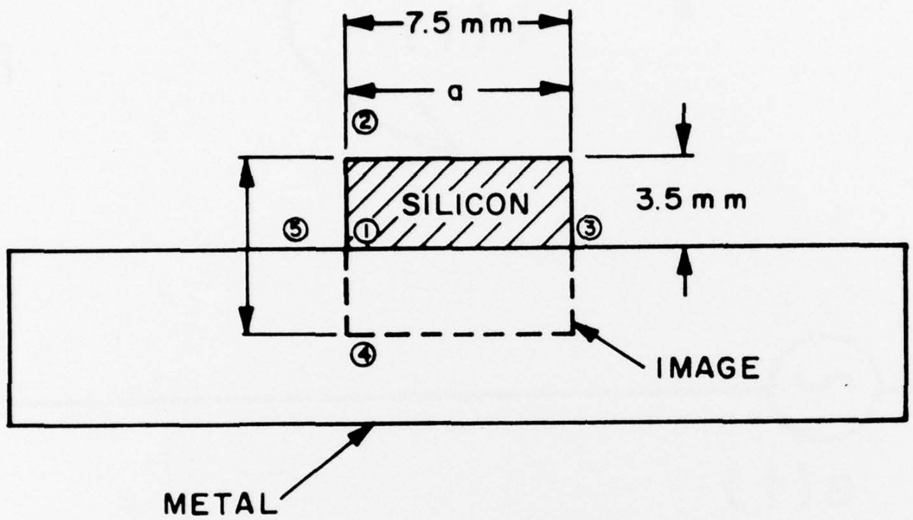


Figure 3. Image-Line Concept for Dielectric Waveguide

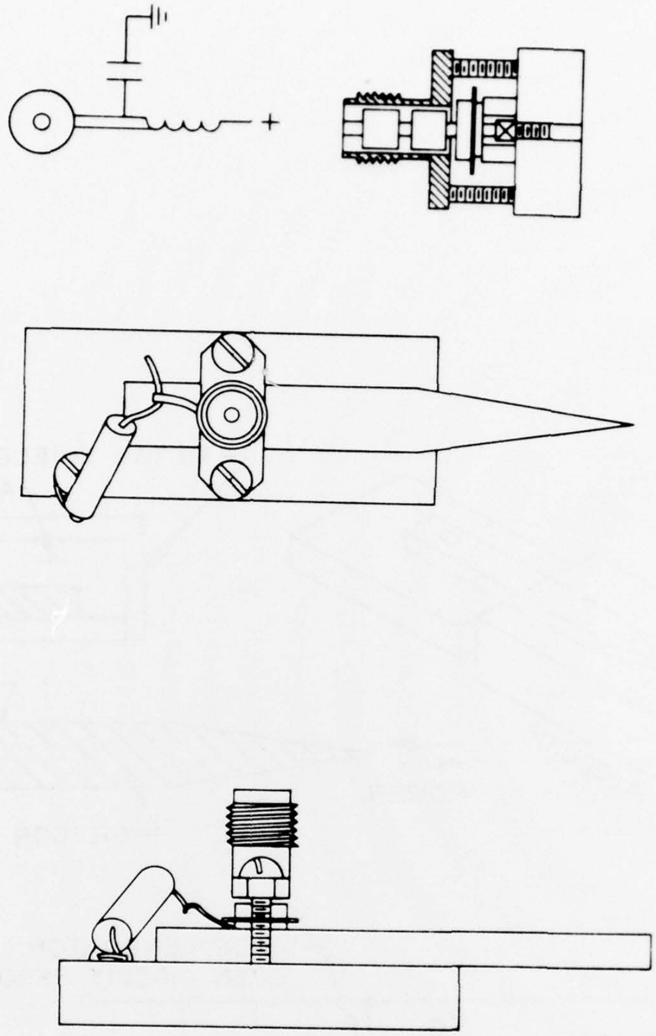


Figure 4. Construction of Ku-Band Oscillator

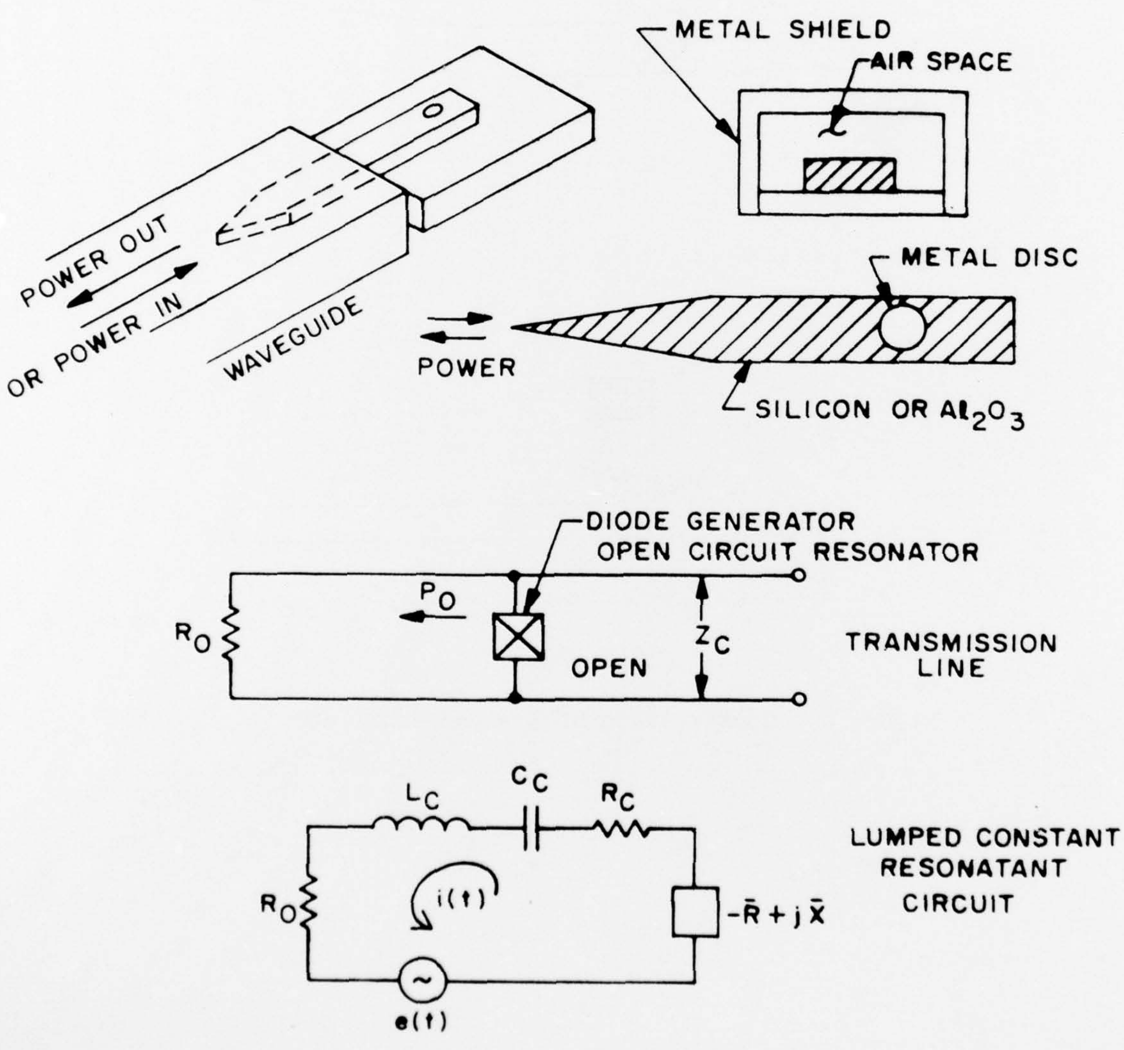


Figure 5. Equivalent Circuits for Dielectric Resonant Oscillator

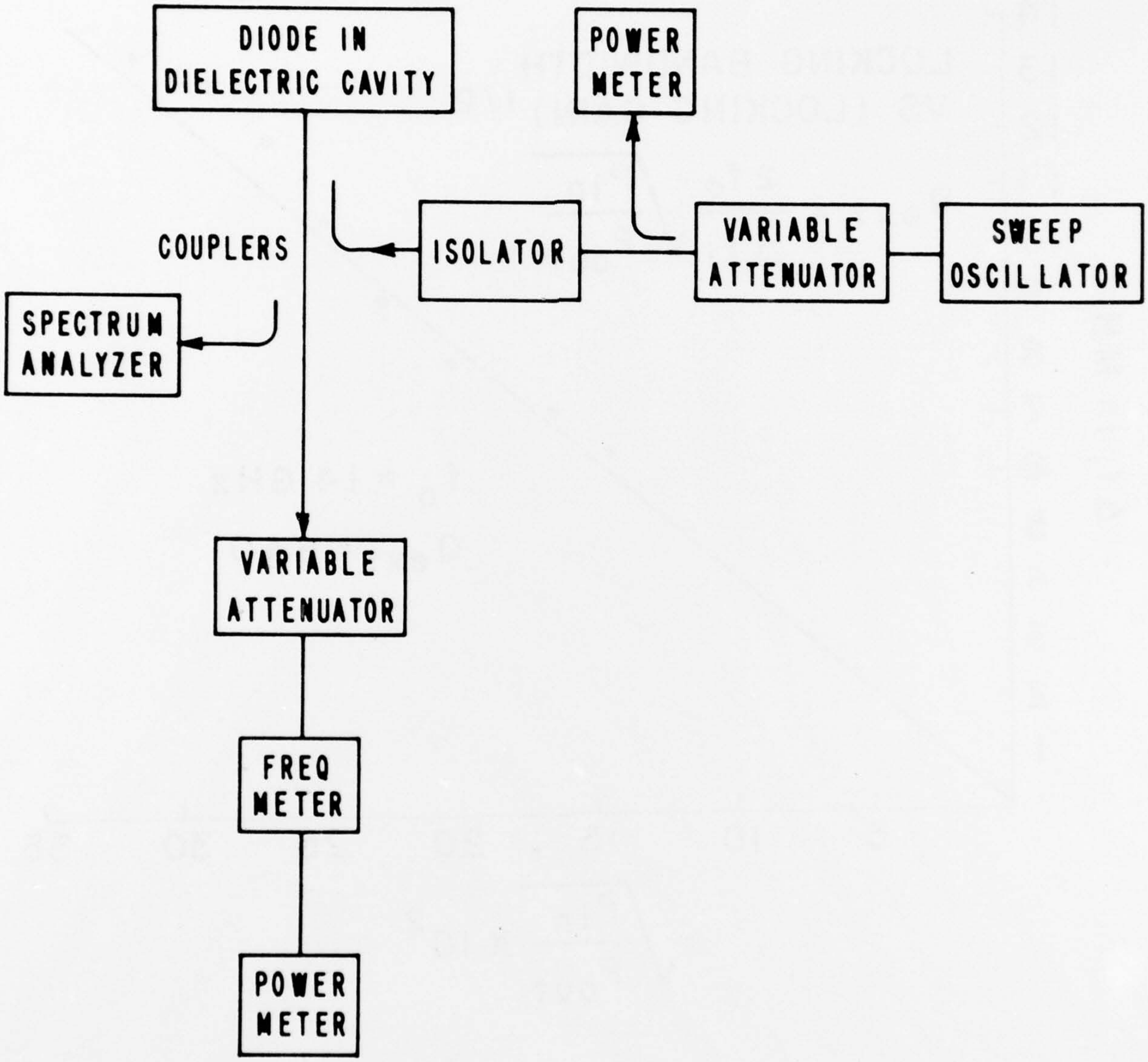


Figure 6. Test Arrangement to Measure Q_{ext}

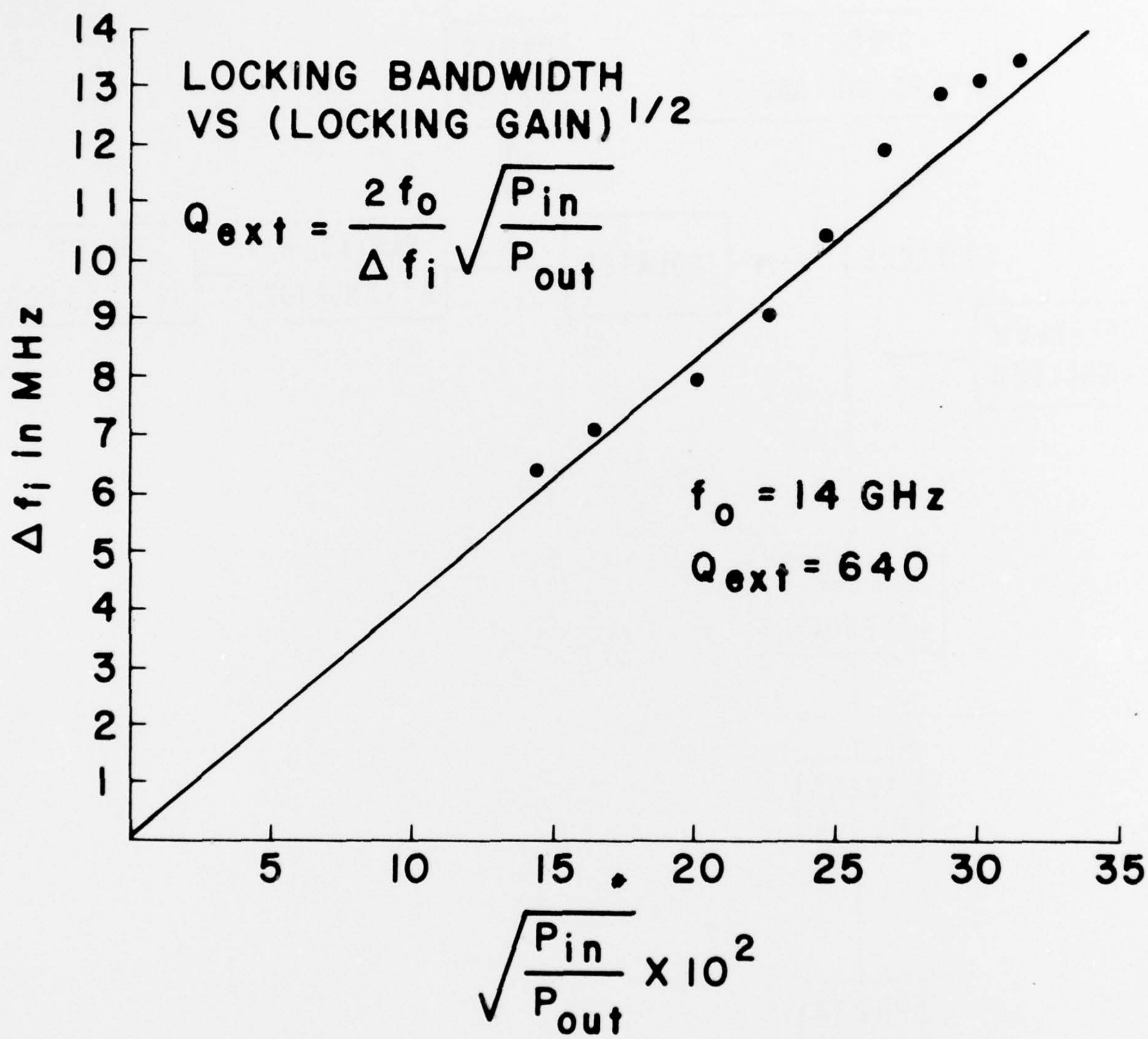


Figure 7. Data for Calculation of Q_{ext}

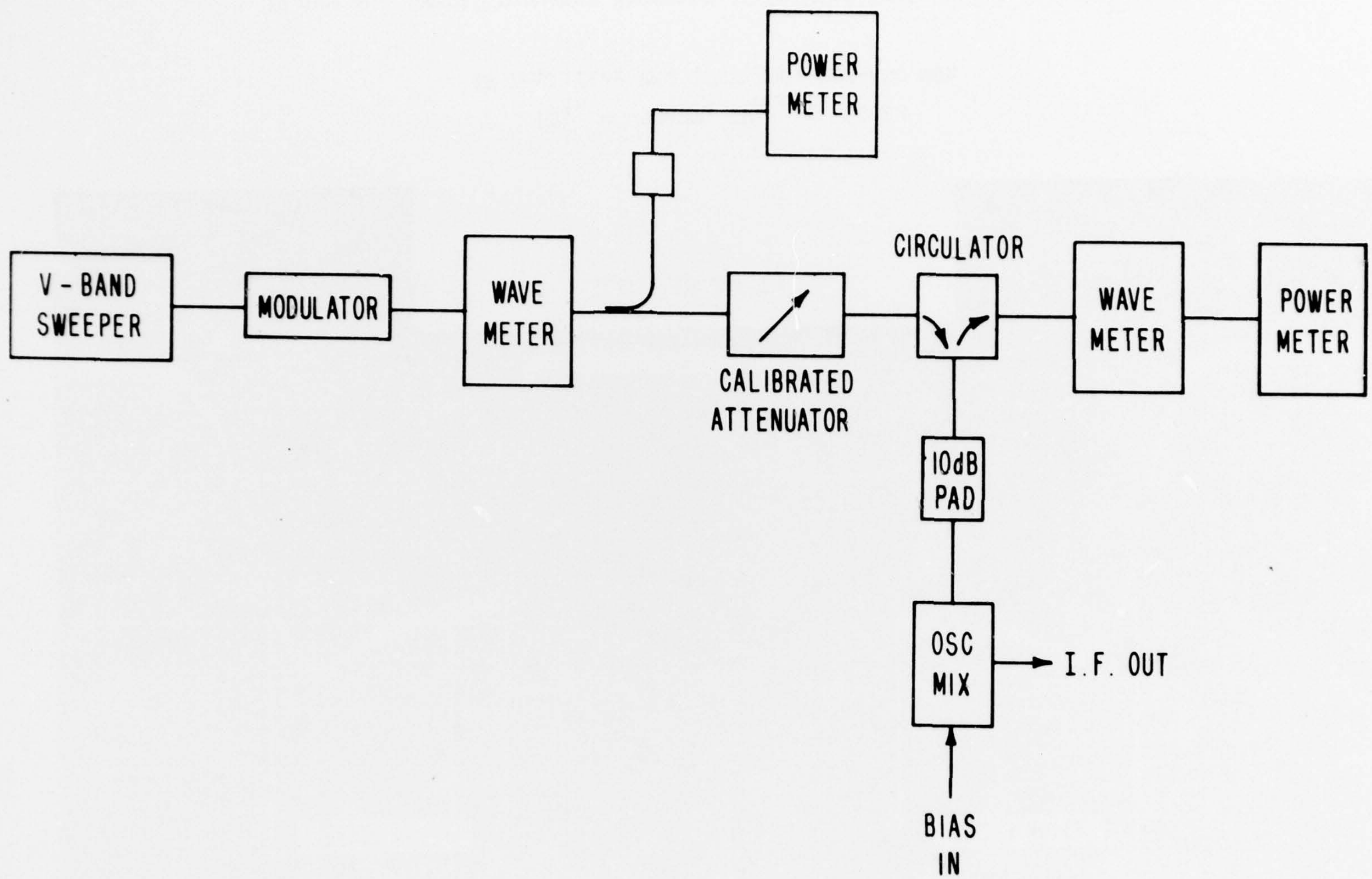
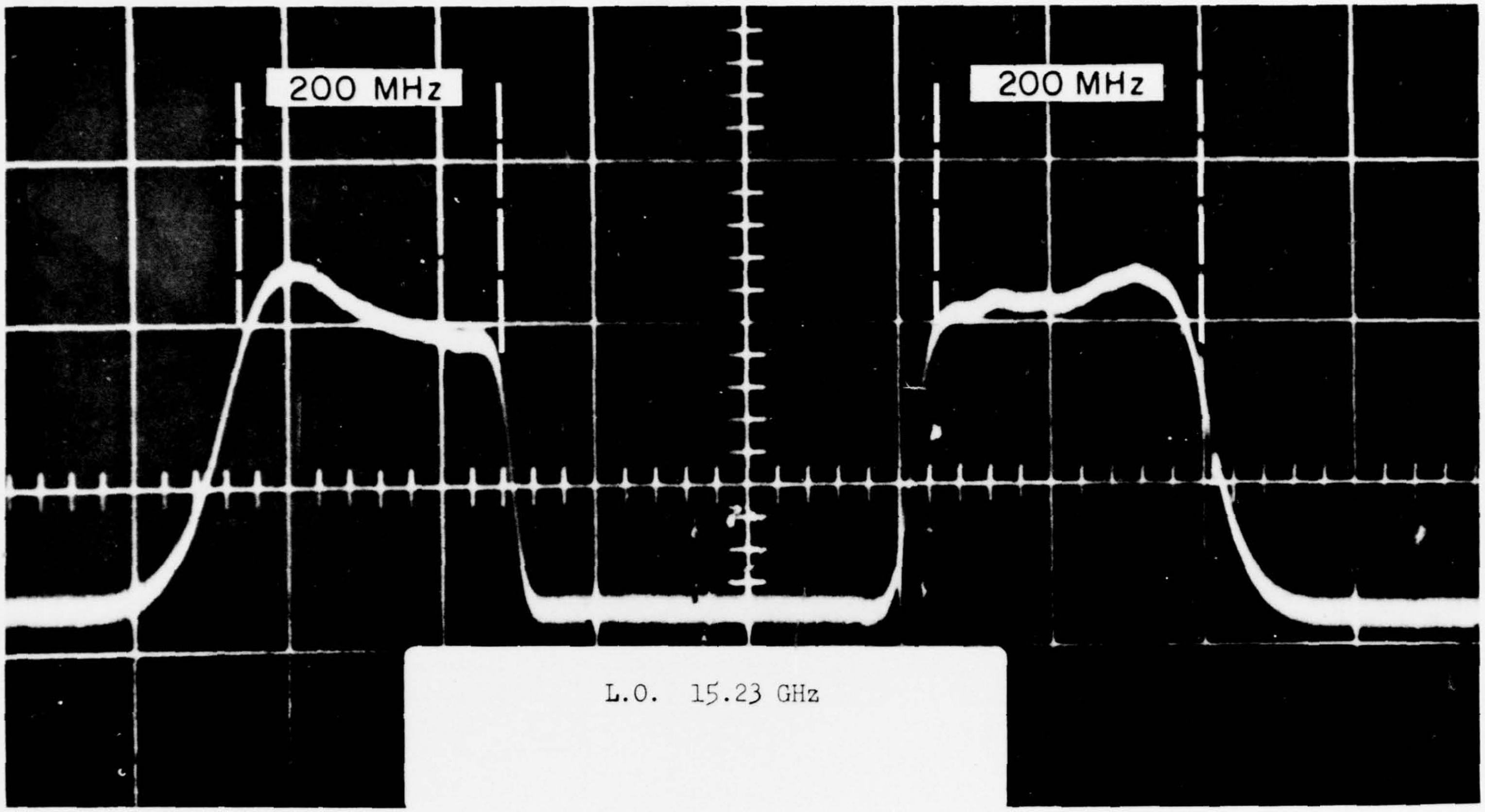


Figure 8. Measurement Circuit for MDS, Conversion Efficiency and Noise Figure



RF_{in} = -50dBM, IF_{out} = -60dBM
IF Amplifier RHG ICLT 300, 200-400 MHz

Figure 9. Swept Frequency Response of Ku-Band Self-Oscillating Mixer

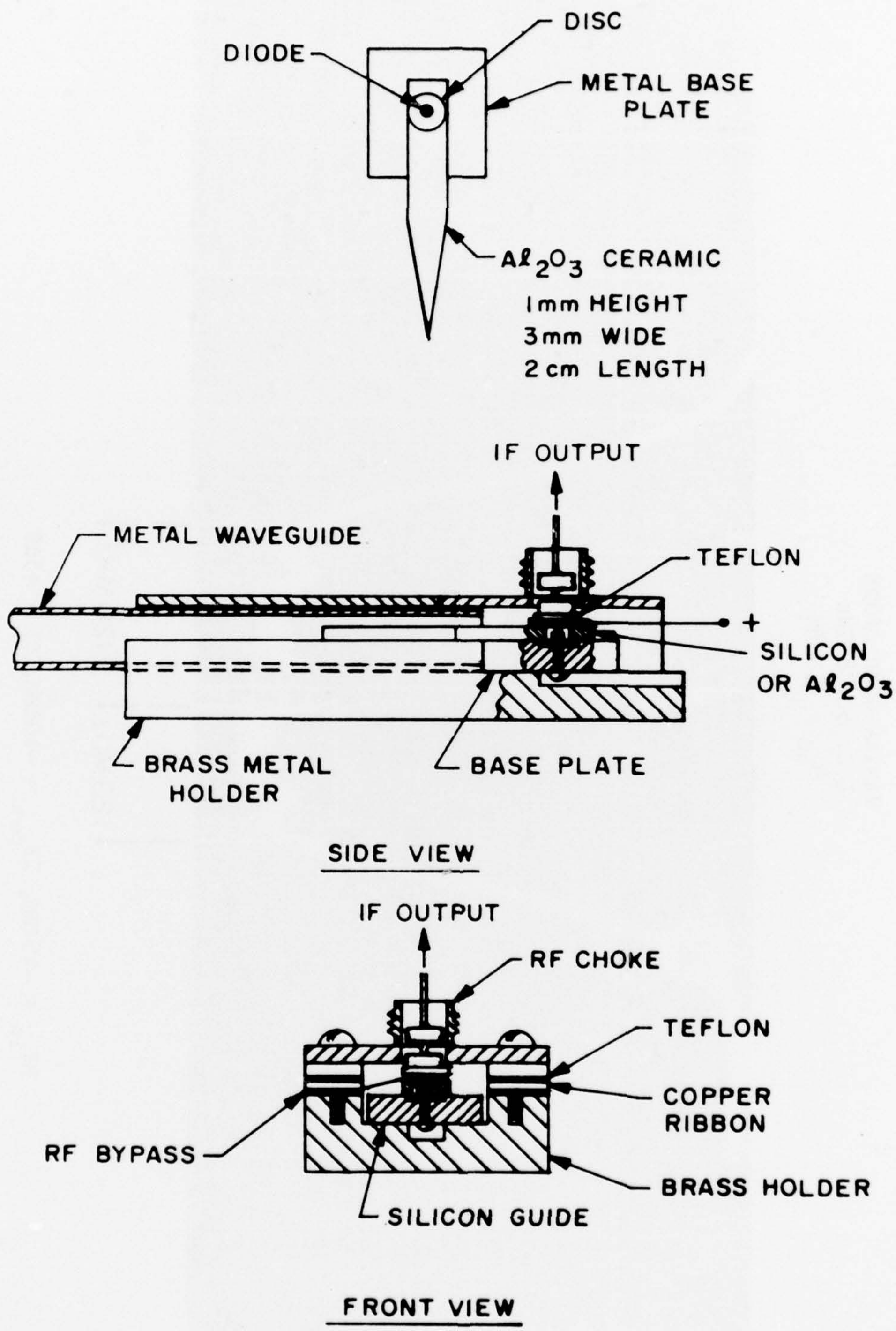
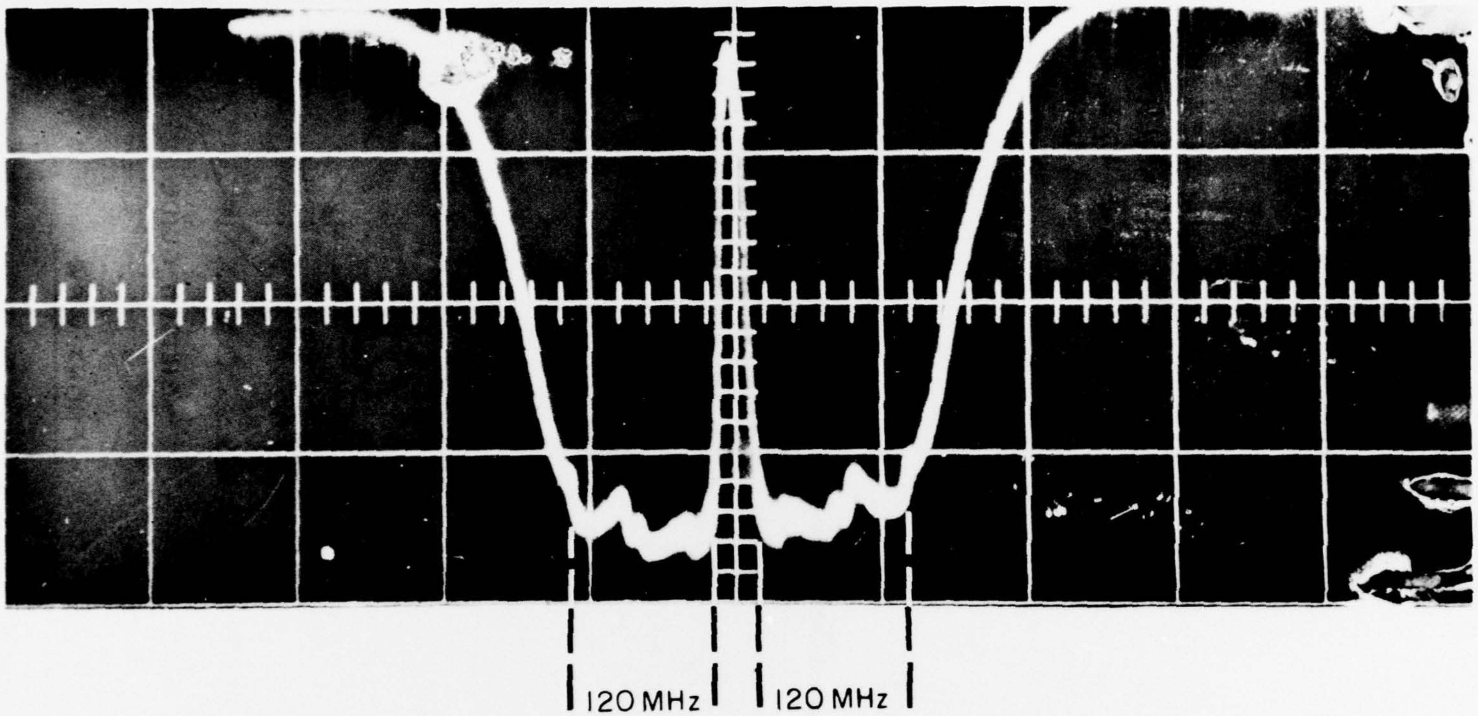


Figure 10. Holder for 60 GHz Dielectric Oscillator

VARIAN GUNN DIODE
L.O. 60.78 GHz
P_{LO} = -10dBM



RF_{in} = -45dBM, IF_{out} = -40dBM, CL = +5dB

IF Amplifier TRONTECH W110B, 1-120 MHz

Figure 11. Swept Frequency Response for 60 GHz Self-Oscillating Mixer